Cerro del Pueblo Fm (Difunta Group, Upper Cretaceous), Parras Basin, southern Coahuila, Mexico: reference sections, age, and correlation

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ABSTRACT

Principal and supplementary reference sections provide data that clarify the stratigraphic relationships and depositional history of the Cerro del Pueblo Formation (CdP) – an important unit in Late Cretaceous paleobiogeographic studies in northeastern Mexico and the Western Interior of North America. At Saltillo, the CdP is 162 m thick, much thinner than previously reported. To the west, however, the CdP thickens to 449 m at Rincón Colorado (35 km west of Saltillo) and 540 m at Porvenir de Jalpa (70 km west of Saltillo). A substantial stratigraphic interval of interbedded grey-green and red beds is present above the CdP throughout the field area; for consistency, it is assigned to the overlying Cerro Huerta Formation (CH).

Westward-thickening of the CdP indicates an increased rate of subsidence and accommodation in that direction, and further suggests that sediment was supplied from the west along a narrow, east–west oriented trough that paralleled the modern Sierra Madre Oriental south of the field area. This trough was likely the location of an embayment in which CdP sediments first aggraded and then slowly prograded to the east and northeast. Overall, the CdP records deposition in very low gradient lower coastal plain and shallow marine (ramp) settings that were influenced by high-frequency changes in relative sea-level and coastal storm events.

Magnetostratigraphic data from 66 samples collected in the Saltillo area indicate that the CdP was deposited in magnetochronozones 32n.3r–32n.2n. This magnetostratigraphic interval falls within the combined Western Interior ammonite biozones of B. reesidei and B. jenseni, and suggests a maximum absolute age of 72.5 Ma for the CdP in the Saltillo area. The Campanian–Maastrichtian boundary (here accepted as 32n–31r) lies 90 m below the top of the overlying CH. A minimum sediment accumulation rate of 55 cm/1,000 yrs is proposed for the CdP.

Key words: stratigraphy, magnetostratigraphy, dinosaurs, Cerro del Pueblo Formation, Cerro Huerta Formation, Difunta Group, Mesozoic, Cretaceous, Coahuila, México.

RESUMEN

A partir de secciones de referencia principales y suplementarias se han obtenido datos que esclarecen las relaciones estratigráficas y la historia de depósito de la Formación Cerro del Pueblo (FCdP), una unidad importante en estudios paleobiogeográficos del Cretácico Tardío en el noreste de

México y en el Interior Occidental de Norte América. En Saltillo, la FCdP presenta un espesor de 162 m, mucho más delgado que lo reportado previamente. Sin embargo, hacia el oeste la formación se engrosa hasta 449 m en Rincón Colorado (35 km al oeste de Saltillo) y 540 m en el Porvenir de Jalpa (70 km al oeste de Saltillo). En muchos sitios del área de estudio, sobreyaciendo a la FCdP se ha detectado un conspicuo intervalo estratigráfico formado por una intercalación de capas gris-verde y rojas, que por consistencia han sido asignadas a la Formación Cerro Huerta (CH).

El engrosamiento hacia el oeste de la FCdP indica un incremento en la tasa de subsidencia y acomodo en esa dirección. También, esto sugiere que el sedimento era aportado desde el oeste, a lo largo de una depresión angosta, orientada este–oeste, ubicada al sur del área de estudio y subparalela a la actual Sierra Madre Oriental. Esta depresión probablemente correspondía a la ubicación de una bahía, en la cual los sedimentos de la FCdP se acumularon primero y después progradaron lentamente hacia el este y noreste. En términos generales, la FCdP registra el depósito en ambientes de planicie costera baja, de muy bajo gradiente y condiciones marinas someras (de rampa) que fueron influenciadas por cambios de alta frecuencia en el nivel relativo del mar y eventos costeros de tormenta.

Datos magnetoestratigráficos de 66 muestras colectadas en el área de Saltillo indican que la FCdP se depositó en las magnetocronozonas 32n.3r–32n.2n. Este intervalo magnetoestratigráfico se ubica dentro de las biozonas combinadas de amonitas del Interior Occidental de B. reesidei y B. jenseni, lo que sugiere una edad máxima absoluta de 72.5 Ma para la FCdP en el área de Saltillo. El límite Campaniano–Maastrichtiano (aceptado aquí como 32n–31r) se ubica 90 m debajo de la cima de la unidad sobreyaciente, Formación Cerro Huerta (CH). Finalmente, se propone una tasa de sedimentación mínima de 55 cm/1,000 años para la FCdP.

Palabras clave: estratigrafía. magnetoestratigrafía, dinosaurios, Formación Cerro del Pueblo, Formación Cerro Huerta, Grupo Difunta, Mesozoico,Cretácico,Coahuila, México.

INTRODUCTION

The Cerro del Pueblo Formation (CdP) in southern Coahuila, Mexico, is famous for its remarkable variety of marine, brackish, and non-marine fossils that includes plants, mollusks, crustaceans, and vertebrates – notably dinosaurs (Wolleben, 1977; Vega and Feldmann, 1991; Rodríguez-de la Rosa and Cevallos-Ferriz, 1994; Hernández *et al.*, 1995; Rodríguez-de la Rosa and Cevallos-Ferriz, 1998; Rodríguez-de la Rosa *et al.*, 1998; Kirkland *et al.*, 2000; Kirkland and Aguillón-Martinez, 2002; Rodríguez-de la Rosa *et al.*, 2002; Eberth *et al.*, 2003). Combined paleontologic and geologic data from the CdP and correlative units in the adjacent La Popa and Sabinas basins provide the most complete picture of North America's southern Late Cretaceous paralic ecosystems and vertebrate communities (*e.g.*, McBride *et al.*, 1975; Kirkland *et al.*, 2000; Brinkman *et al.*, 2002), and thus the CdP and its fossil assemblages are critical in studies of Late Cretaceous paleobiogeographic patterns in the Western Interior of North America (*e.g.*, Lehman, 1987; 1997; 2001). However, there remain fundamental stratigraphic problems that require resolution before the strata and fossil assemblages of the CdP can be placed and fully appreciated in the context of a North American or global stratigraphic framework.

First, it is no longer possible to effectively use the stratotype section of the CdP (see original location in Murray *et al.*, 1962, fig. 4) due to a combination of very poor exposure and extensive encroachment of the city of Saltillo into the type area (Figure 1C). Without reference to a type section, it is difficult to constrain, compare and correlate the CdP's fossil assemblages and its other stratigraphic data sets (*e.g.*, magnetostratigraphy) with other locations in the Parras, La Popa, and Sabinas basins, and throughout the Western Interior of North America.

Second, the redefinition of the CdP by McBride *et al.* in 1974 appears to have inadvertently adjusted the placement of the CdP upper contact (*cf.* Murray *et al.*, 1962), thus requiring a revision of the stratotype.

Third, the precise age of the formation and its fossil assemblages still remain uncertain with respect to the Campanian–Maastrichtian boundary. Although most workers refer to the CdP as Campanian in age, others regard the precise age of the formation as uncertain, referring to it as Campanian–Maastrichtian (*e.g.*, Hernández *et al.*, 1995; Soegaard *et al.*, 1997; Arney, 1998, p. 11; also see discussion in Kirkland *et al.*, 2000). These interpretations are largely based on previously presented biostratigraphic data and, to our knowledge, no independent chronostratigraphic data are available to assess these interpretations.

Fourth, our examination of the CdP's stratigraphy and paleoenvironments in the southern Parras Basin (Figure 1) suggests far more stratigraphic variation and complexity in this unit than has been previously appreciated, especially in relation to its stratigraphic thickness and relationship with the overlying Cerro Huerta Formation. Given the remarkable multikilometer thickness of the Upper Cretaceous sedimentary package in this region, fossiliferous units such as the CdP offer unique opportunities to evaluate high resoution litho-, bio-, and chronostratigraphic patterns

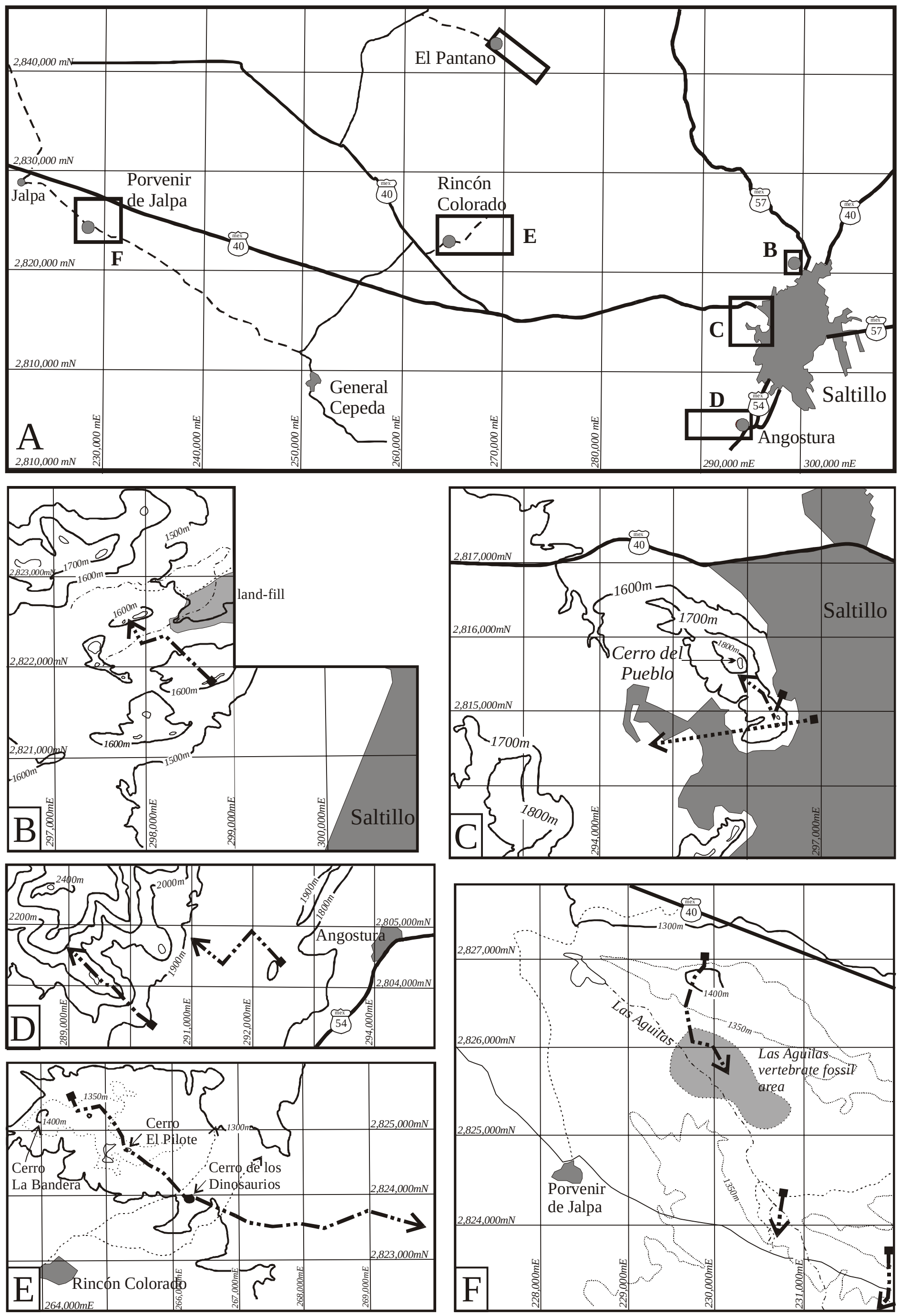

Figure 1. Location of study areas (for location in Mexico, see Figure 3). A: overall study area (datum NAD27); rectangles indicate the investigated areas. B–F: study areas shown in A, except El Pantano. In B and F, the datum is ITRF92 (equivalent to NAD 83/WGS 84); in C–E the datum is NAD27. Dashed-dotted arrows indicate the locations and directions of measured sections. The dotted arrow in C represents the location of the original stratotype section of the CdP as determined from Murray *et al.* (1962, fig. 4). Ten-kilometer scale grid in A; one-kilometer scale grids in B–F.

during the Late Cretaceous of southwestern North America (*e.g.*, Ye, 1997). As more of the CdP's dinosaur and other vertebrate assemblages are studied, a revised and reliable stratigraphic framework is required to facilitate comparison of the CdP's fossils and strata within and beyond the limits of the Parras Basin.

In this paper we (1) present a principal and two supplementary reference sections for the CdP; (2) describe new aspects of the formational geometry across the southern portion of the basin; and (3) present magnetostratigraphic data to assist in more precisely determining the age of the CdP, and correlating its vertebrate localities and strata within and beyond the Parras Basin. It is also our intent that our data can be used to test previous genetic stratigraphic (sequence stratigraphic) interpretations of Upper Cretaceous strata in the Parras, La Popa, and Sabinas basins (*e.g.*, Soegaard *et al.*, 1997; Ye, 1997).

GEOLOGICAL FRAMEWORK

The CdP is the basal formation in the multi-kilometer-thick Difunta Group (Figure 2; Murray *et al.*, 1962; Weide and Murray, 1967; McBride *et al.*, 1974; Soegaard *et al.*, 1997; Kirkland *et al.*, 2000). The Difunta Group and the underlying Parras Shale were deposited eastward and northward of the arcuate fold-and-thrust belt – the Sierra Madre Oriental (Fig. 3). The CdP and the Difunta Group were defined by Murray *et al.* (1962) and redefined by McBride *et al.* (1974), and subsequent workers have provided more detailed information about aspects of the stratigraphy, petrology and paleoenvironments in the Difunta Group and its correlates (*e.g.*, McBride *et al.*, 1975; Hill, 1988; Vega-Vera *et al.*, 1989; Soegaard *et al.*, 1997; Ye, 1997; Arney, 1998; Halik, 1998; Lawton *et al.*, 2001). Difunta Group strata in the southern part of the Parras Basin in and around Saltillo and to the west consist of an approximately 4,000 meter thick package of alternating marine, brackish and freshwater sediments that were sourced from and deposited east and north of the Sierra Madre Oriental (Figure 3). Redbeds dominate non-marine portions of the sections, but are also present locally in brackish and even marine sections (Weide and Murray, 1967).

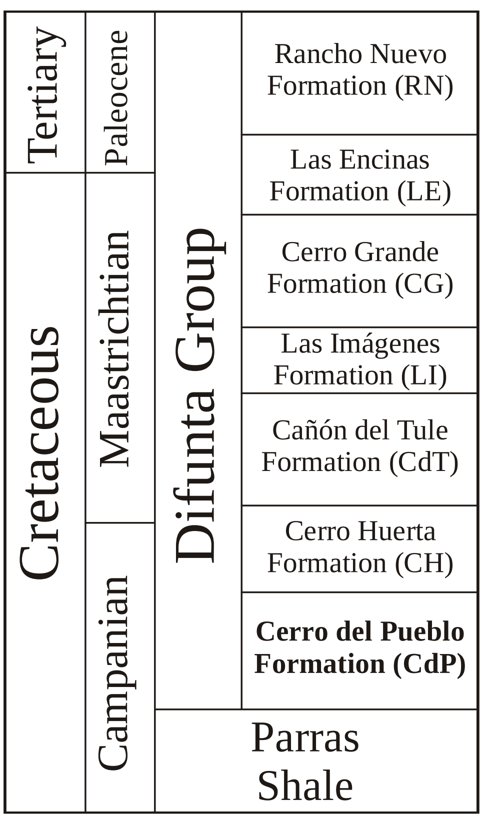

Figure 2. Stratigraphic chart showing the formational divisions and age of the Difunta Group. Formational abbreviations as used in the text.

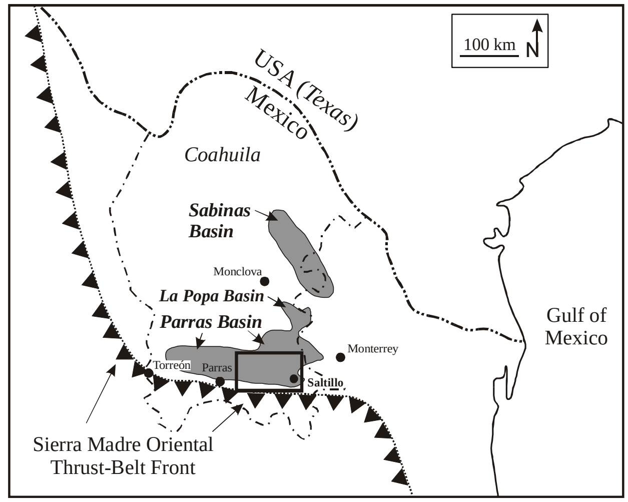

Figure 3. Regional geographic, tectonic, and basinal contexts of study area (rectangle).

The Sierra Madre Oriental fold-and-thrust belt developed in response to westward subduction of dense oceanic lithosphere beneath the Guerrero magmatic arc (Ye, 1997) and was active episodically from the Early Cretaceous (Valanginian) through to the Eocene. The extremely large accommodation that preseved the multi-kilometer-thick Difunta Group probably reflects the great density of subducted lithosphere (Ye, 1997). Difunta Group strata were structurally altered by eastward migration of the fold-and-thrust belt during the early Tertiary (Weide and Murray, 1967). Today, Difunta Group strata are deeply jointed, folded, and locally faulted. CdP exposures to the west (as far as the original type area of the Difunta "formation" near Parras [Imlay, 1936]) exhibit increasingly severe structural deformation (including overturned folds and imbricated thrust faults) and thus become increasingly difficult to correlate, even locally.

REFERENCE SECTIONS

Murray *et al.* (1962, p. 377) first defined the CdP. They placed its lower contact with the Parras Shale at the base of the thickest sandstone–siltstone unit that overlies the calcareous shales and siltstones of the Parras Shale in Saltillo, and placed its upper contact with the Cerro Huerta Formation (CH) at "...the top of the massive siltstone which occurs 310 m stratigraphically higher." At the CH stratotype section, 10 km south–southwest of Saltillo near the village of Angostura (Figure 1D), Murray *et al.* (1962, fig. 3) placed the CdP–CH contact at the top of a prominent siltstone–sandstone body that forms the base of stepped ridge (referred to as Cerro Huerta by them, but unnamed on recent topographic maps [INEGI, 1999]). Above this bed, the stratigraphic section is dominated by redbeds with only locally-developed reduced sediments, especially beneath sandstones. However, throughout the southern Parras Basin area our stratigraphic studies reveal that the CdP–CH transition is not marked by a sharp transition to redbeds. Instead, we have consistently recorded a transitional stratigraphic zone – tens of m thick – that consists of interbedded grey-green and red sediments (Figure 4) and shows a gradual increase in the number and thickness of redbeds upsection. This transitional interval was not described by Murray *et al.* (1962), but it is clear from their reported thickness of the CdP in Saltillo (310 m) and their pick for the base of the CH near the village of Angostura that the transitional interval was included (intentionally or unintentionally) within the CdP.

McBride *et al.* (1974, p. 1609) 'redefined' (*sensu* NACOSN, 1983, Article 18) the formations of the Difunta Group but accepted the locations of the formational stratotypes of Murray *et al.* (1962). They excluded all redbeds from the CdP and placed the CdP–CH contact at "...the base of the first red or green bed…". However, by so doing they inadvertently lowered the CdP–CH contact of Murray *et al.* (1962) and 'revised' (*sensu* NACOSN, 1983, Article 19) the CdP and its stratotype. Although the basal contact of the CdP with the Parras Shale is plainly exposed in the stratotype area (near the top of Cerro del Pueblo), urban encroachment of the city of Saltillo prevents examination of most of CdP composition or its upper contact with the CH, and precludes any accurate determination of the CdP stratotype thickness or other stratigraphic attributes (*e.g.*, age range). Because of the need to update our understanding of the CdP stratotype for intrinsic and comparative purposes, we established a Principal Reference Section (NACOSN, 1983, Article 8e) approximately 7 km north of the stratotype in an area called La Escondida (INEGI, 2002). Although we accept the revision of the CdP by McBride *et al.* (1974), we add to it here with our measured Principal and Supplementary Reference sections and lithofacies descriptions (Appendix 1).

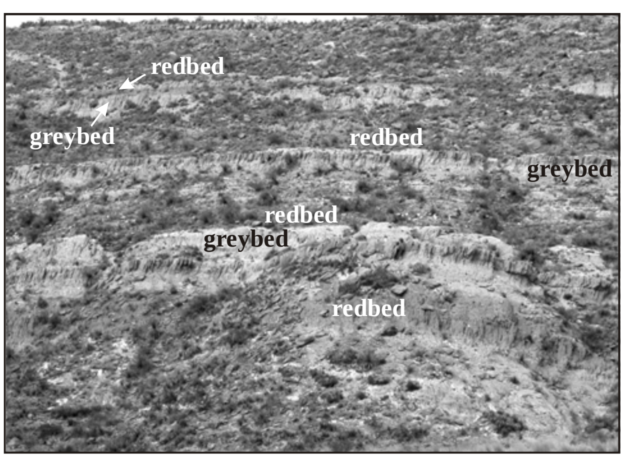

Figure 4. Rhythmically alternating red and grey mudstones, and sandstones in the basal portion of the Cerro Huerta Formation at La Escondida. Resistant ledges are up to 1.5 m thick.

The Cerro del Pueblo Principal Reference Section at La Escondida

Figure 1B shows the location of the Principal Reference Section at La Escondida, north of Saltillo and west of Highway 57 in an area of northeast–southwest oriented cuestas. The advantages of designating this location as a Principal Reference Section are: (1) both the lower and upper formational contacts are plainly exposed; (2) it exhibits a nearly continuous exposed section; (3) there are thick and continuous exposures of the Parras Shale and Cerro Huerta formations below and above the CdP, respectively, that can be easily correlated elsewhere in the area; and (4) the remaining formations of the Difunta Group (Cañón del Tule, Las Imágenes, Cerro Grande, Las Encinas, and Rancho Nuevo) are all visible in semi-continuous outcrop north of here. The area is most easily accessed through trails that diverge west from State Highway 57 and end in an abandoned landfill site. Inhospitable plant cover, deep weathering and erosion, desert varnish and structural alteration provide significant challenges for measuring sections in this region. Strata dip steeply (up to 25º) toward the north–northwest, and are best exposed along south–southeast facing slopes below resistant calcareous sandstones. A prominent right lateral strike-slip fault bounds the reference section area to the west. To the east, beds dip into the subsurface just west of Highway 57.

At La Escondida, the CdP is 162 m thick and consists of numerous multimeter-thick coarsening-upward massive mudstone deposits that culminate in invertebrate shell coquinas and/or sandstones (Figure 5). The base of a prominent 24 m thick fine- to medium-grained sandstone body marks the bottom of the formation, and sharply overlies a sandier- and thickening-upward succession of calcareous shale, siltstone and minor sandstone at the top of the Parras Shale (6A). The sandstone body is tabular, forms a prominent ridge-top marker around Saltillo, and corresponds to the original base of the CdP as defined by Murray *et al.* (1962). The top of the section is marked by the first occurrence of redbeds mudrock (5R 4/2; RCCC, 1948). Beds are typically tabular and laterally extensive (Figure 6B), and the section consists of a complexly interbbeded succession of seven lithofacies (Appendix 1). Colors are typically grey, brown, tan, and green. Fresh- and brackish-water plant, invertebrate and vertebrate fossils are abundant throughout the section. In contrast, marine invertebrate

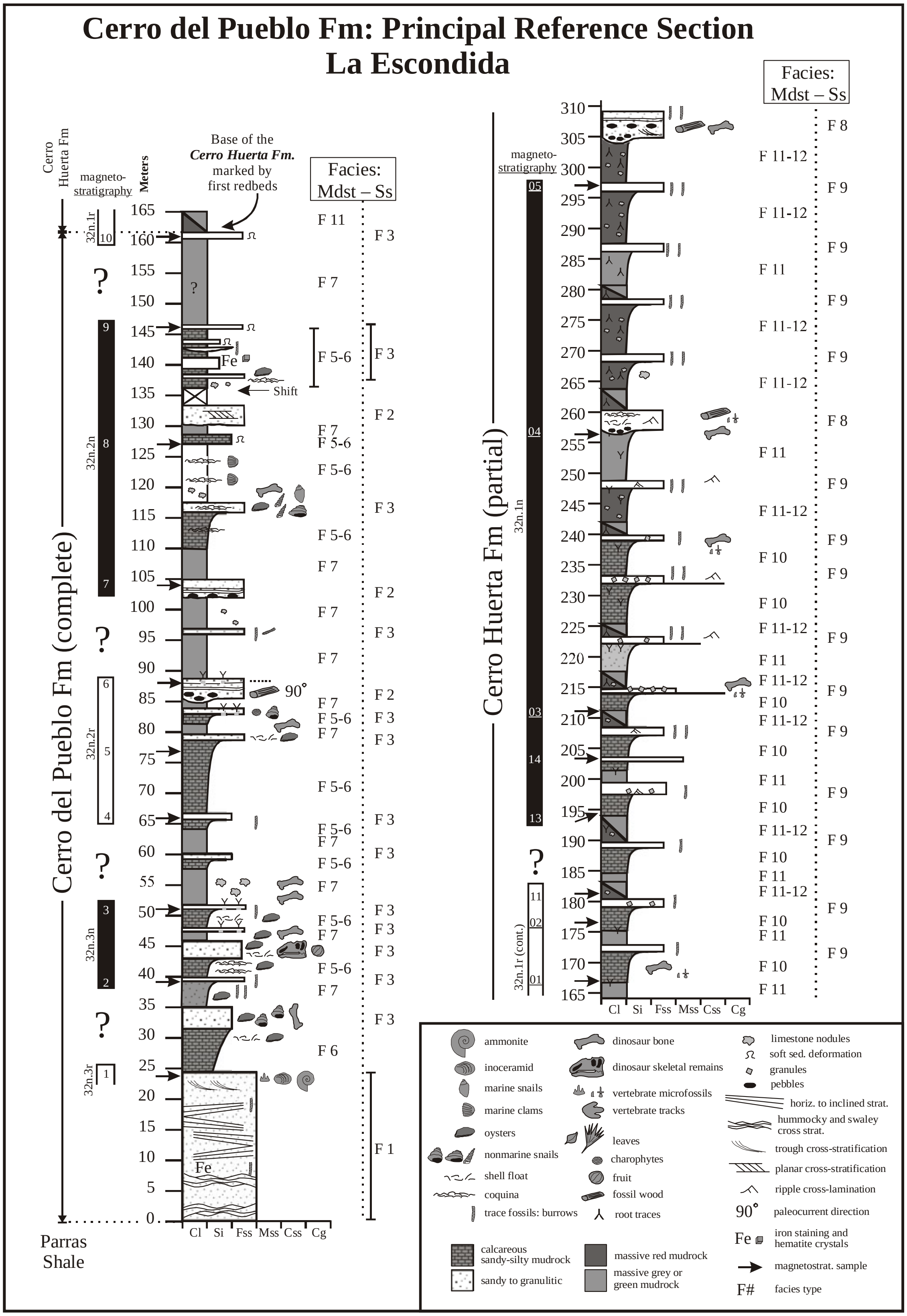

Figure 5. Measured Principal Reference Section at La Escondida. Black and white column left of the measured section shows our interpretation of the magnetostratigraphic samples (numbers; see also Figure 10). Letters and numbers to the right of sections (*e.g.,* F 7) indicate facies types as described in Appendix 1. Lightly shaded intervals indicate grey and green mudrock; dark shading indicates redbeds. Triangular light and dark shading indicates interbedded grey-green and red mudstones. Abbreviations: Mdst, mudstone; Ss, sandstone; Cl, claystone, Si, siltstone, Fss, Fine grained sandstone, Mss, medium grained sandstone, Css, coarse grained sandstone, Cg, conglomerate.

fossils (consisting of ammonites, inoceramids, pelecypods and gastropods) are concentrated in two discrete zones: one at the top of the basal sandstone (15–24 m), and the other in the upper one-third of the section (115–125 m). Invertebrate trace fossils are particularly abundant throughout the section and consist of a complex variety of feeding and dwelling traces that we tentatively attribute to crustaceans.

Supplementary Reference Section #1: Rincón Colorado

Rincón Colorado is an important vertebrate fossil producing area 36 km west of Saltillo, just north of undivided Highway 40 (Figure 1A; Kirkland *et al.*, 2000). Good exposures of the CdP are present locally — especially below resistant ledges and ridges — and patterns of weathering and plant cover, and surface concentrations of fossils provide additional stratigraphic data from extensive covered intervals. A composite stratigraphic section (Figure 7) was measured along a 6 km transect (Figure 1E). Along transect, beds dip consistently 5º to 11º toward the east (azimuthal range 50º to 125º). Although folds and thrust faults were noted in the Rincón Colorado area (as per all areas of the southern Parras Basin), the transect crosses no displacements.

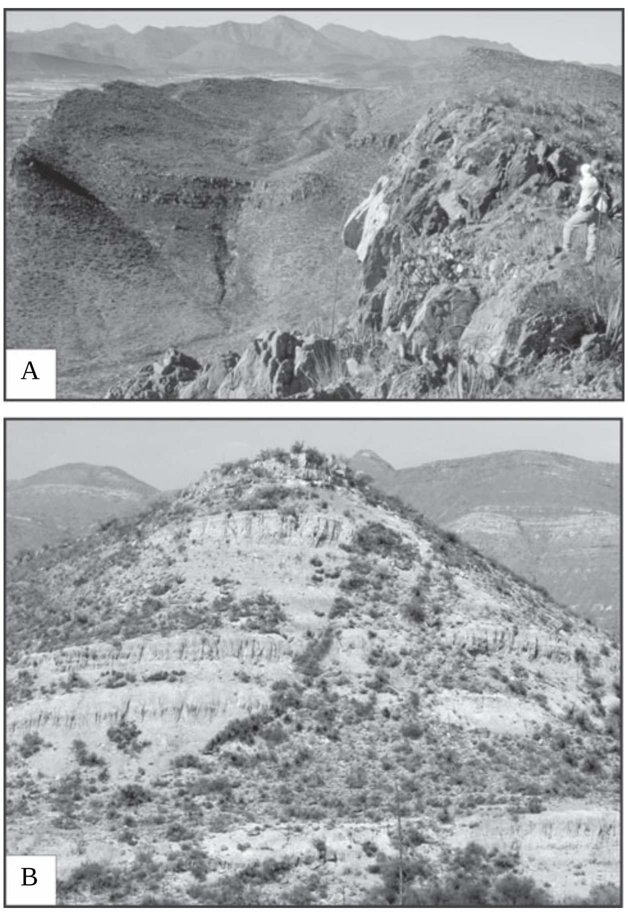

Figure 6. Outcrop at La Escondida Principal Reference Section. A: Basal sandstone of the CdP. Note folded basal sandstone in the distance. B: Down-dip (into photo) view of rhythmically alternating, fine- and coarse-grained facies of the CdP. Section thickness is approximately 25 meters and includes the measured section interval 43–65 m in Figure 5.

The Cerro del Pueblo Formation is 449 m thick at Rincón Colorado (Figure 7), nearly three times its thickness at La Escondida. Kirkland *et al.* (2000; fig. 9) report a thickness of 190 m for the CdP section at Rincón Colorado and, thus, significantly underrepresented its actual thickness. The base of the Supplementary Reference Section at Rincón Colorado is marked by a 20 m thick, multistoried sandstone body that sharply overlies the coarsening- and thickening-upward siltstones and sandstones of the Parras Shale; it forms the cap rock at Cerro La Bandera. The upper one-half of this sandstone yields localized concentrations of inoceramid shell and fossil wood, and granulitic to pebbly lenses with marine-to-brackish-water vertebrate microfossils. The top of the CdP at Rincón Colorado is marked by the first occurrence of red-brown mudrock (449 m), a few hundred meters east of an area of interpretive trails and the richly fossiliferous site known locally as “Cerro de los Dinosaurios”. The CdP section at Rincón Colorado exhibits a complex stratigraphy of richly fossiliferous and interbedded, massive grey mudstones, grey-green calcareous sandy mudstones, siltstones, and sandstones like those present in the La Escondida Principal Reference Section. It also exhibits numerous discrete intervals that are rich in dinosaur or other vertebrate fossils (200m, 335m, 392m, 420–445m), tracks (185m, 334m), and marine fossils such as ammonites, inoceramids and a variety of marine pelecypods and gastropod coquinas (20m, 91m, 285m, 399m).

Supplementary Reference Section #2: Las Águilas

Supplementary Reference Section 2 (Figure 8) was compiled approximately 70 km west of Saltillo (Figure 1 A and F), north–northeast of Porvenir de Jalpa in an area that we call ‘Las Águilas’ — the name of an ephemeral creek that runs through the middle of the transect. The Las Águilas Reference Section is exposed discontinuously along a 4 km transect and, as is typical of more western localities, exposures are patchy and generally poor. Along transect, dip ranges from 0º (at the Las Águilas fossil locality, see below) to 25º with an azimuthal range of 160–195º. A linear east–west ridge marks the position of an increase in dip (up to 60º) along the southernmost kilometer of the transect, and likely indicates that there is an east–west trending thrust fault displacement (Figure 8, 282 m). However, we observed similar thicknesses for the CdP throughout this region and, thus, do not regard the potential for displacement as significant in this section.

The CdP–Parras Shale contact is not exposed at the

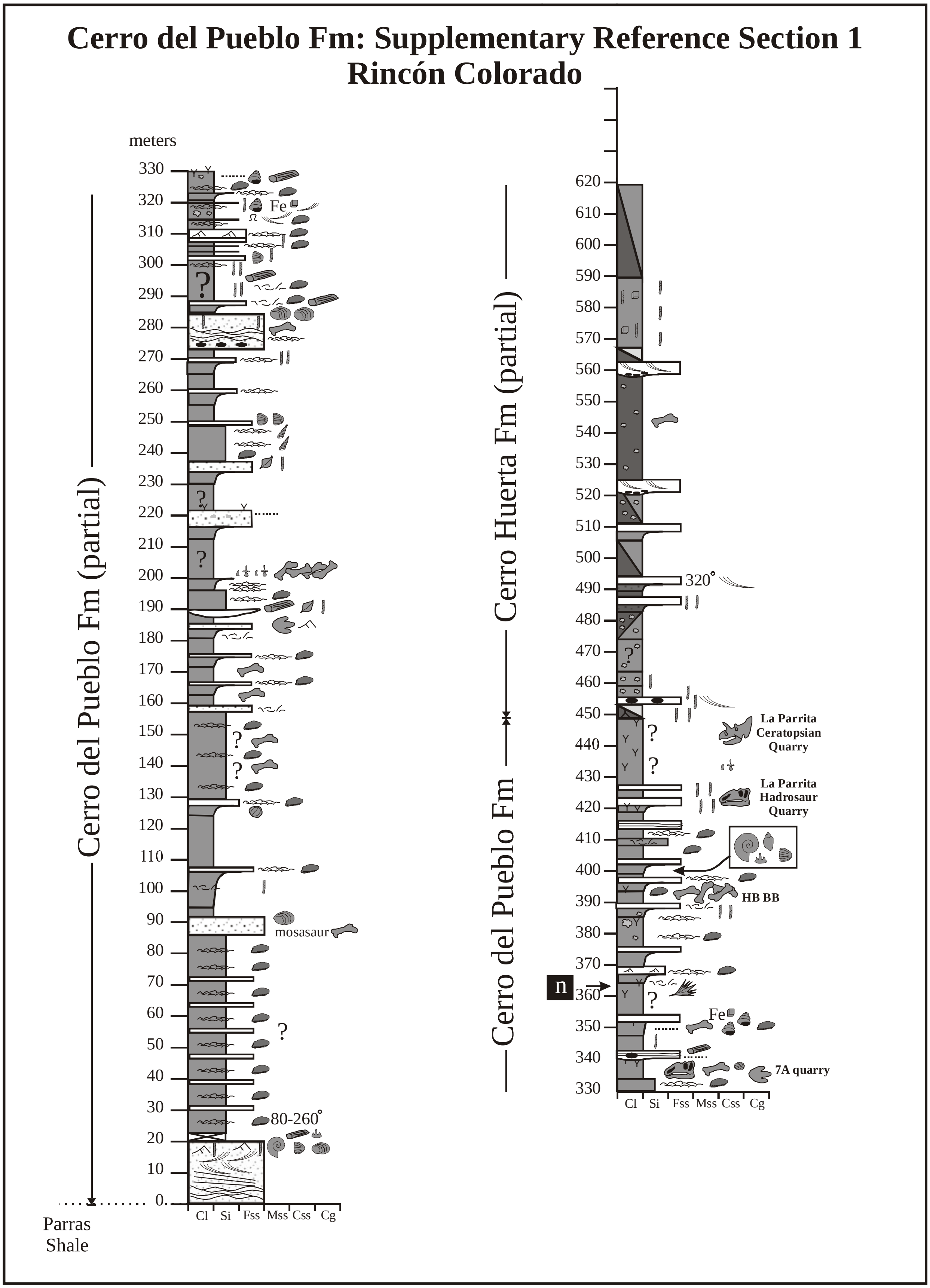

Figure 7. Measured Supplementary Reference Section (#1) at Rincón Colorado. All abbreviations as in Figure 5. "**n**" refers to a magnetostratigraphic sample with a normal polarity.

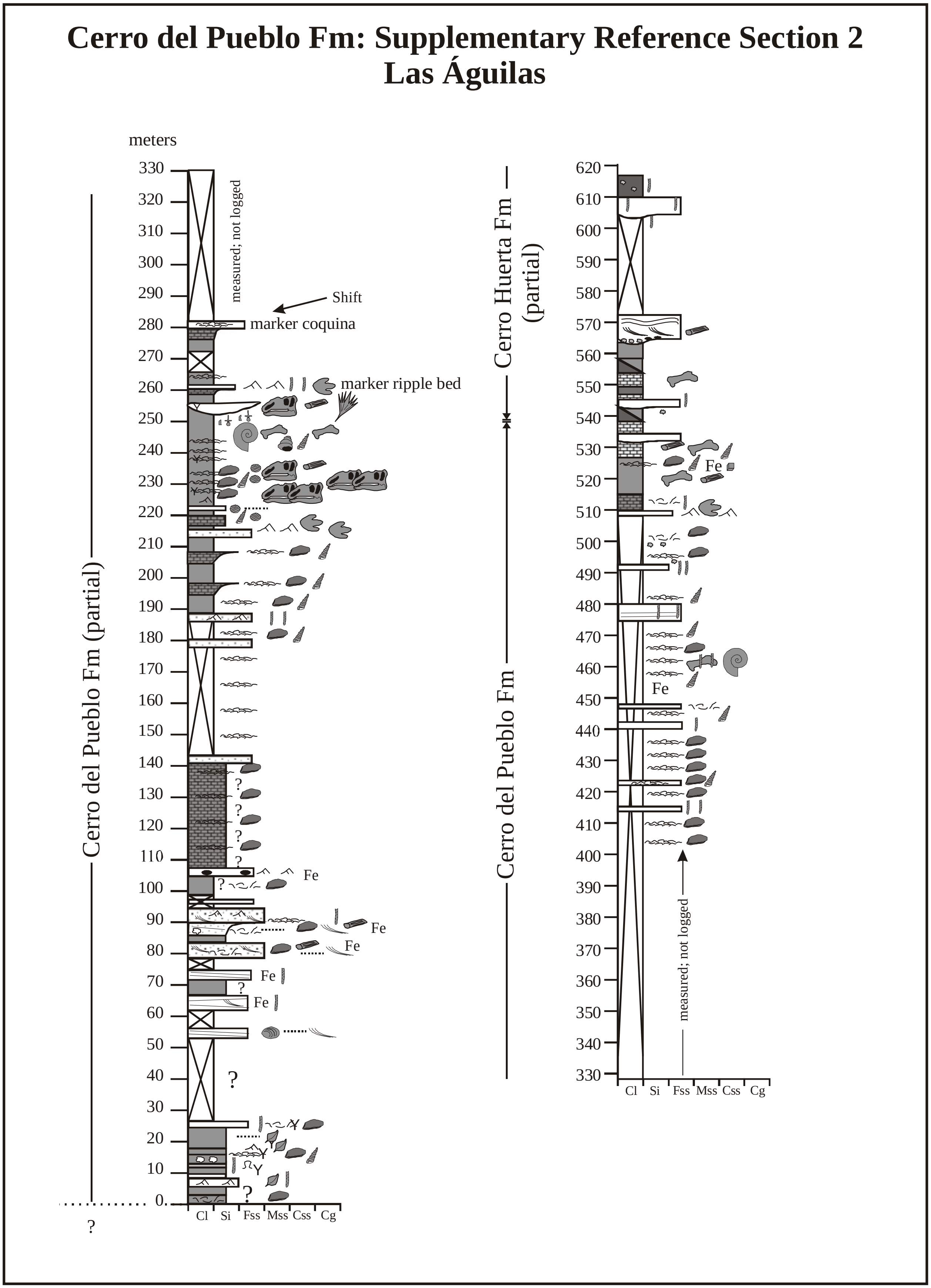

Figure 8. Measured Supplementary Reference Section (#2) at Las Águilas. All abbreviations as in Figure 5. Note the thick, non-redbeds interval.

base of this section (northern flank of Cerro de Angostura; INEGI, 2002), and thus, we interpret the measured thickness of the CdP in the Las Águilas section (540 m) as a minimum. The top of the CdP is placed at the first occurrence of red-brown mudrock, and can be easily identified throughout the area, especially for a few kilometers along the road that runs east from the village of Porvenir de Jalpa (INEGI, 2002). The CdP is at least 90 m thicker here than at Rincón Colorado, continuing its westward-thickening trend from Saltillo.

As at all known localities in the Parras Basin, the CdP section at Las Águilas exhibits a complex interbedded succession of coarse- and fine-grained facies that are dominated by brackish-water invertebrates (in particular, oysters). Similar to the section at Rincón Colorado, it has numerous discrete stratigraphic intervals dominated by sandstones (50–98 m), non-marine vertebrates (222–255 m; 520–530 m), and marine invertebrates (55 m; 245 m; 460 m). The section includes an unusually rich zone of vertebrate fossils (skeletons, tracks and trackways) from 215–261 m that is referred to as the "Las Águilas locality" by Eberth *et al.* (2003) and Rodríguez-de la Rosa *et al.* (2003).

Cursory examination of strata farther west, near the village of Jalpa and the town of Parras, indicate that although CdP strata are present (*e.g.*, Imlay, 1936), comparative thicknesses and stratigraphic patterns are not readily discernable due to extreme structural deformation.

Measured Sections: El Pantano and Angostura

In addition to the measured reference sections described above we also examined exposures of the CdP and CH at El Pantano and Angostura (Figure 1 A and D), measuring the thickness of the CdP and CH at each location. The contact between the Parras Shale and CdP, and basal sandstones of the CdP are excellently exposed in an arroyo just east of El Pantano. Throughout this area, beds dip as much as 20º towards the east (azimuth 80º–90º). In this section, a 50 cm thick red mudstone bed occurs stratigraphically 175 m above the base of the CdP, technically marking the contact with the CH. Above this bed, grey-green beds typical of the CdP predominate for 60 m, with a zone of well-developed interbedded grey-green and red strata first occurring at 235 m. The succession becomes dominated by redbeds 360 m above the base of the CdP. We place the CH–Cañón del Tule contact 930 m above the base of the CdP.

At Angostura, south of Saltillo, a similar pattern was observed. There, beds dip 20º to the WNW (azimuth 310º). At 155 m above the base of the CdP there is a thin red mudstone unit that marks the contact with the CH. A thick grey-green interval predominates above this, and interbedded grey-green and red sediments do not appear until 230 m above the base of the CdP. A redbeds-dominated succession begins 160 m higher at 390 m. We place the CH–Cañón del Tule contact 1,036 m above the base of the CdP.

GEOMETRY AND CORRELATION OF THE CERRO DEL PUEBLO FORMATION ALONG THE SOUTHERN MARGIN OF THE PARRAS BASIN

Figure 9A displays two cross sections. In each, the CdP–CH contact is used as a horizontal datum. Section a–a' is 70 km long and extends W–E from Las Águilas to La Escondida. There is a pronounced westward thickening of the CdP and a slight westward thickening of the variegated (lower) CH. As shown in Figure 9B, this pattern indicates higher rates of subsidence and greater accommodation to the WSW. This interpretation is consistent with regional reconstructions that show NNW–SSE oriented shorelines from Texas into northeastern Mexico (Lehman, 1997, 2001) parallel to the western fold-and-thust belt. South of Saltillo, however, the fold-and-thrust belt and shoreline became oriented east–west (*e.g.*, McBride *et al.*, 1974, 1975; Soegaard *et al.*, 1997; Ye, 1997; Goldhammer and Johnson, 1999) and although many of the river systems originated along the flanks of the Sierra Madre Oriental and flowed to the north in this area (Weide and Murray, 1967, fig. 9), the formational geometry of the CdP indicates that most sediment was transported from the areas to the west, probably by means of a major axial alluvial trunk system that was established and maintained parallel to the southern fold-and-thrust belt (*e.g.*, Miall, 1981; Ye, 1997). The tectonic and sequence stratigraphic history of the region has been described in terms of a foreland basin with a southern foredeep and northward-thinning sequences that were developed largely in response to changes in relative sea-level (*e.g.*, Ye, 1997, figs. 3-6). However, our data indicate that a high rate of subsidence to the west and south resulted in the accommodation of this extremely thick clastic succession, and probably was responsible for maintaining the position of the east–west alluvial trunk system.

Ye (1997) regarded the Parras foredeep in front of the Sierra Madre Oriental as anomolously deep relative to foredeeps that developed east of the Andes and the Cordillera thrust belts, and suggested the possibility that these thick deposits ultimately developed in response to complex tectonics and patterns of sedimentation associated with the tectonic alteration of the Guerrero terrane. He also interpreted the arcuate geometry of the Sierra Madre thrust belt as "…mainly controlled by [a] preexisting embayment along the continental margin." (Ye, 1997, p. 128). As indicated above, our data support these interpretations and suggest that there was a west–east oriented trough that extended from Parras to Saltillo, through which westward- and southward-derived clastics were distributed to the east. Within the western portion of this trough, sediment supply and subsidence must have remained essentially balanced during deposition of the lower portions of the Cerro del Pueblo Formation, forming a long-lived, vertically-aggrading lower coastal plain and shoreline system. Ultimately, sediment supply exceeded accomodation and resulted in the eastward and northward progradation of the coastal plain shallow marine system through the Saltillo region.

The facies and stratigraphic data (Figures 5, 7, 8, and Appendix 1) all suggest that the CdP sediments were deposited on a low-gradient and broadly homogenous coastal plain, that included small, low-sinuosity channels, levees, plant-rich wetlands (*e.g.*, salt marshes, Frey and Basan, 1978), as well as lakes, ponds, and lagoons/bays

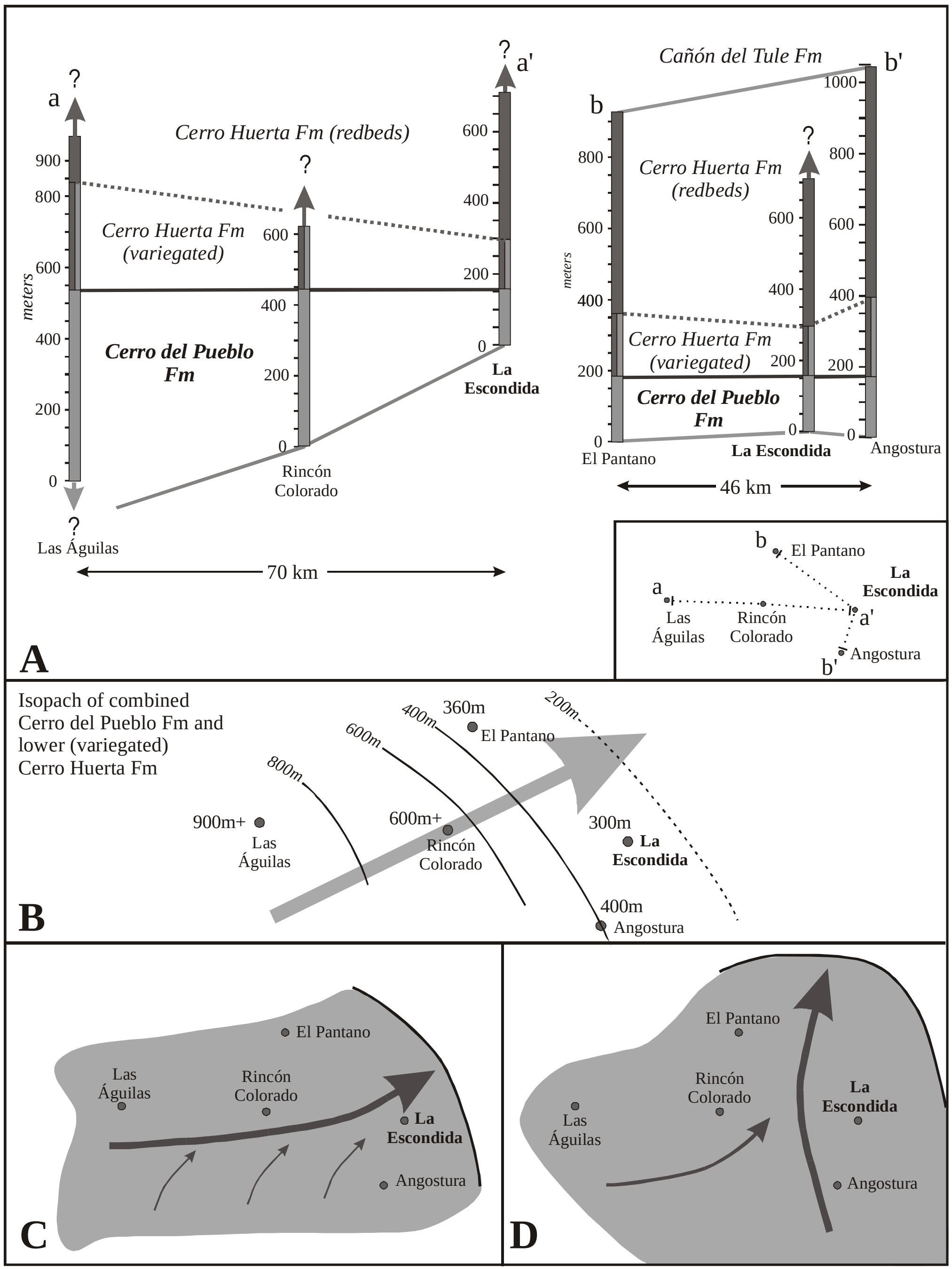

Figure 9. Schematic cross-sectional geometry of the CdP and CH. A: west–east (a–a') and northwest–southeast (b–b') cross sections. Locations shown in inset and Figure 1. Horizontal datum is the Cerro del Pueblo–Cerro Huerta formational contact as indicated by the first occurrence of redbeds. B: Isopach map of combined CdP and variegated (lower) CH formations. Arrow indicates inferred direction of clastic progradation. C: Inferred directions of sediment transport during deposition of the CdP constructed from our data and previously published data. D: Directions of sediment transport during deposition of the CH as interpreted from McBride *et al.* (1974, 1975).

(*cf.*, McBride *et al.*, 1975), and bounded seaward by shoreface and possibly, delta front sands (*e.g.*, Hill, 1988). The discrete stratigraphic intervals that yield rich assemblages of marine fossils and massive beds of brackish-water taxa (*e.g.*, oysters) indicate the occurrence of high-order transgressive–regressive episodes and/or extreme storm events that punctuated the overall regressive succession.

The isopach map shown in Figure 9B displays a pattern considerably different than that indicated by McBride *et al.*, (1974, fig. 11; 1975, figs. 19, 28) and provides little evidence for the existence of a delta. We restricted our isopach to a "stratigraphic slice" that records only the overall regressive portion of the combined CdP–CH succession. Accordingly, we combined the CdP and the variegated (lower) portion of the CH. We excluded the redbeds-dominated portion of the CH because we were unable to retreive reliable thickness data from all of our localities. When our data are compared with those presented by McBride *et al.* (1974, 1975), the data sets support the interpretation that the lower Difunta Group in the southern Parras Basin consists of sediments deposited during two distinct phases of clastic wedge progradation: 1) an early phase (CdP–variegated CH) when subsidence was highest to the west and clastics prograded slowly to the east, filling in the trough from west of Parras to Saltillo (Figure 9C); and 2) a later phase (redbeds-dominated CH) when the zone of greatest subsidence had shifted toward the east and clastics prograded to the north in the Saltillo region, forming a vast clastic wedge (Figure 9D; as per McBride *et al.*, 1974, fig. 11).

AGE OF THE CERRO DEL PUEBLO FORMATION

Figure 10 shows the results of magnetostratigraphic analyses conducted on 66 samples collected from measured sections in the Saltillo area (Parras Shale at Cerro del Pueblo, the CdP and lower CH at La Escondida, and the upper CH and lower CdT at Angostura, Figure 1). Samples were collected by hand and oriented with a Brunton compass set at 0º magnetic declination. Sample spacing was determined in part by the availability of appropriate samples, outcrop quality, and earlier published conclusions about rates of sediment accumulation. We attempted to collect one sample every 25 m, believing this to represent a temporal spacing of approximately 25,000–75,000 years (see discussion below).

Samples were analyzed at the Department of Earth and Atmospheric Sciences, University of Alberta, with a Molspin magnetometer, which has a minimum sensitivity of about 5x10^{11} A·m^{2}. Alternating field (AF) demagnetization was done using a two-axis tumbler in steps of 5 mT (milliteslas). The samples that show a reversed polarity have a relatively light normal polarity overprint due to the Earth's modern magnetic field. This is illustrated in Figure 11, which shows the magnetic behavior of samples from six sites (three reversed and three 3 normal) in the middle of the CdP where sampling density was greatest. Although magnetic direction in the reversed samples before

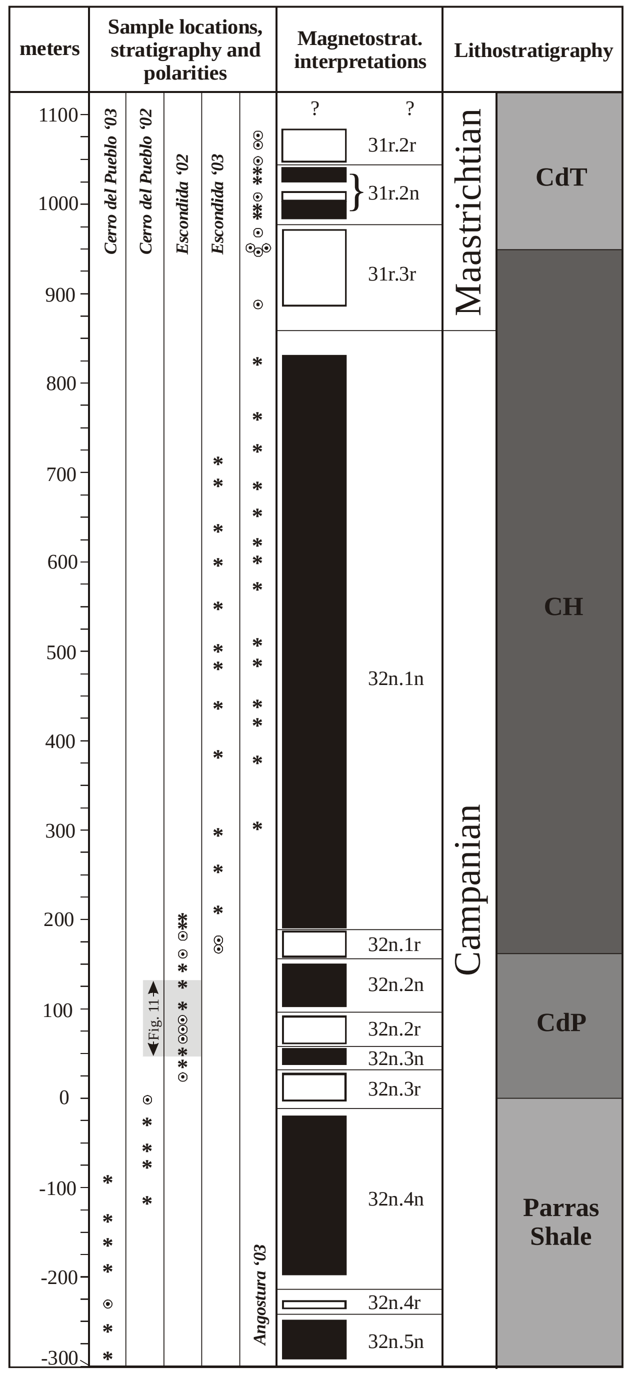

Figure 10. A preliminary composite magnetostratigraphy of the Lower Difunta Group based on samples collected from the Saltillo area at Cerro del Pueblo, La Escondida, and southwest of Angostura. Asterisks represent samples with normal polarities. Open circles with dots represent samples showing reversed polarities. Black bars represent magnetically normal intervals; white bars indicate magnetically reversed intervals. For magnetostratigraphic interpretations see text and Lerbekmo and Braman (2002).

demagnetization is usually normal, the direction becomes reversed at 10–20 mT of demagnetization. Samples that have normal characteristic polarity, on the other hand, show little change in inclination at these demagnetization levels. Samples from reversed sites at the base of the Cañón del Tule Formation (950–975 m, Figure 10) behave similarly to those from the CdP, either having a reversed polarity before demagnetization or becoming reversed at 10 mT.

The interpretation presented in Figure 10 is based on existing biostratigraphic placement of the CdP and comparison of our magnetostratigraphic data with those of Lerbekmo and Braman (2002; fig. 14). Specimens of *Inoceramus vanuxemi* are locally abundant throughout the CdP at Rincón Colorado and La Escondida (see Kirkland *et al.*, 2000). According to Kauffman *et al.* (1993) the range of *I. vanuxemi* may extend from *B. gregoryensis* up into the basal range of *B. jenseni* (Kauffman *et al.*, 1993, fig. 11) and thus, *I. vanuxemi* can be regarded as a middle through late Campanian 'index' fossil. The middle through late Campanian is characterized by two long normal chronozones: 33n and 32n (Gradstein *et al.*, 1995).

Our data (Figure 10) reveal a long normal with one short reversal in the upper portion of the Parras Shale at Cerro del Pueblo, overlain by a succession of three reversals and two normals that extends through all of the CdP and into the lower CH at La Escondida. We also recognize a very long normal through most of the CH at La Escondida and Angostura, and a modest reversal at the top of the CH and base of the Cañón del Tule Formation (CdT) at Angostura. A nearly identical pattern has been recognized in the well-documented magnetochron interval 32n–31r from the Red Deer River Valley in southern Alberta (Lerbekmo and Braman, 2002, fig. 14). In Alberta, five reversed polarity subzones have been identified in 32n. The presence of four small-scale reversed polarity subzones and a long normal polarity zone above these in the composite section from the Saltillo area suggests that the CdP section at La Escondida is correlable with the Late Campanian magnetochron interval that extends from 32n.3r at the base up through 32n.2n in Alberta. This magnetochron interval falls within the combined *Baculites reesidei* and *B. jenseni* ammonite zones (Lerbekmo and Braman, 2002), which has

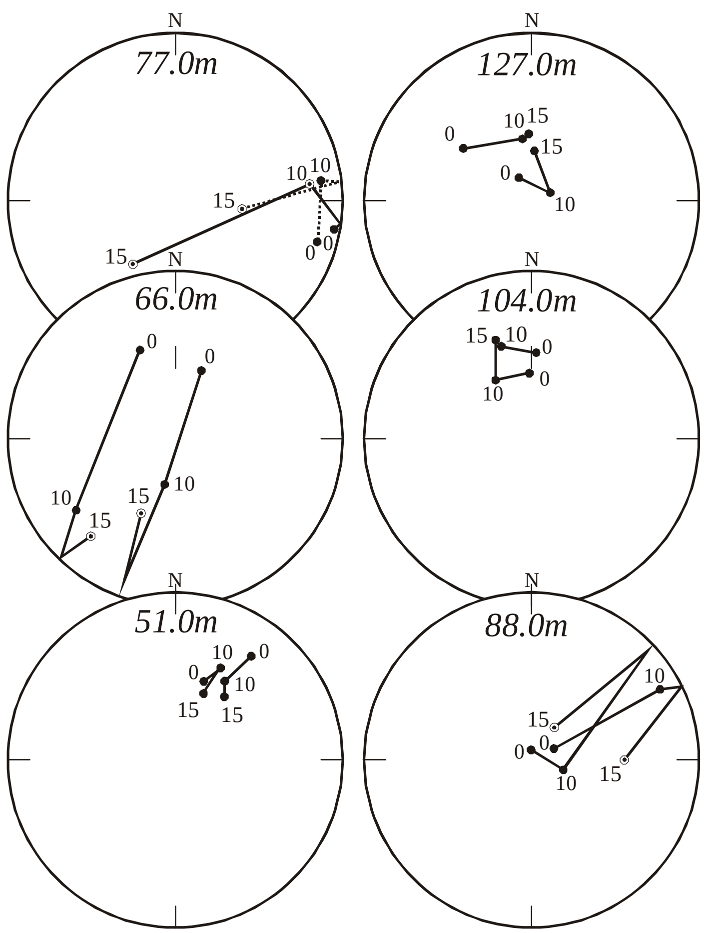

Figure 11. Stereographic polar projections showing the magnetic behavior of samples during alternating field (AF) step demagnetization. Two samples are shown from each of six horizons (three normal polarity; three reversed polarity) from the CdP. Solid dots plot on the lower hemisphere (normal polarity); open circles with dots plot on the upper hemisphere (reversed polarity). Small numbers are demagnetization level in milliteslas. Large numbers in italics are the relative stratigraphic positions of the samples in meters (see Figure 10).

an absolute age range of 72.5–71.5 Ma according to Obradovich (1993), and 72.4–71.4 Ma according to Kauffman *et al.* (1993, fig. 11). Thus, these data provide a maximum age of 72.5 Ma for the CdP.

Comparison with the Red Deer River section of Lerbekmo and Braman (2002) indicates that most of the CH in the Saltillo region occurs within normal polarity zone 32n.1n, and that the Campanian–Maastrichtian boundary (defined here as the 32n–31r polarity zones boundary; see Lerbekmo and Braman, 2002) occurs approximately 90 m below the contact between the CH and CdT. Although the pattern of polarities above the CH–CdT contact matches the Red Deer River section quite well, the absence of data from above our measured sections and the possibility that the basal CdT may be disconformable (Halik, 1998) indicate that further work, beyond the scope of our project, is required to confidently interpret this and higher parts of the section.

Our data and comparisons with the Red Deer River section can be used to test previous interpretations that rates of sediment accumulation were very high in the CdP and Difunta Group in general (*e.g.*, Kirkland *et al.*, 2000). The time span of 32n is not agreed upon in the recent Polarity Time Scales (Harland *et al.*, 1990; Cande and Kent, 1992; Berggren *et al.*, 1995), but the mean is about 2.3 Ma. The lowest complete subzone sampled to date in the Parras Basin is believed to be 32n.4r. In the Cypress Hills of southern Alberta, 22 percent of the thickness of 32 n lies below the base of 32n.4r (Lerbekmo and Braman, 2002). In the Parras Basin, the thickness of 32n from its top to the base of 32n.4r is 1,065 m. Adding another 20 percent indicates that the total thickness of 32n is about 1,300m. This gives a compacted sediment accumulation rate of approximately 55 cm/1,000 yrs. Clearly, sections of the CdP and the Difunta Group represent unique opportunities to collect and assess very high-resolution stratigraphic data.

In the CdP we collected 11 samples through 162 m of section for an average sample spacing of 15 m, and an average time spacing of 27,000 yrs. Through the composite section shown in Figure 10, our average sample spacing was 21 m, and our average time spacing was 38,000 yrs. Our lowest density sampling was conducted near the top of the CH. There, samples were spaced as much as 63 m, representing a time spacing of as much as 115,000 years. Given that polarity reversals typically occur on a time scale of 10^{4-7} years, we are confident that the results presented here are of sufficiently high resolution to be used effectively in local, regional, and global correlation.

SUMMARY

1) Principal and supplementary reference sections, measured sections and sedimentologic data clarify the stratigraphic definition and relationships of the CdP throughout the southern portion of the Parras Basin. A consistently developed interbedded succession of grey-green and redbeds that has been previously overlooked is assigned to the overlying CH.

2) The CdP thickens dramatically to the west, from Saltillo to Porvenir de Jalpa.

3) Pronounced westward thickening of the CdP parallel to the modern Sierra Madre Oriental fold-and-thrust belt indicates an increased rate of subsidence and accommodation in that direction, and the likely existence of a trough through which sediment was supplied to the east.

4) The CdP aggraded vertically in the west and then, at a later stage, prograded slowly to the east and northeast. Sediment dispersal directions were apparently reoriented strongly NNE during deposition of the overlying CH.

5) A limited suite of seven broad facies shows that the CdP sediments were deposited in lower coastal plain and shallow marine settings that were strongly influenced by high frequency changes in relative sea-level and/or coastal physical processes (*e.g.*, storm events).

6) Magnetostratigraphic data from 66 samples from the CdP in the Saltillo area indicate that there the unit was deposited in magnetochronozones 32n.3r–32n.2n. This range falls within the combined Western Interior ammonite biozones *B. reesidei* to *B. jenseni*, and indicates a maximum absolute age of 72.5 Ma for the CdP in the Saltillo area.

7) It is likely, but as yet unproven, that the CdP–Parras Shale contact becomes older to the west.

8) At Angostura, south–southwest of Saltillo, the Campanian–Maastrichtian boundary occurs in the upper CH, 90 m below the CH–CdT contact.

9) The CdP and CH, and probably other formations in the Difunta Group, are characterized by very high rates of sediment accumulation (*e.g.*, 55 cm/1,000 yrs). These formations thus provide unique opportunities to collect very high-resolution stratigraphic data.

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APPENDIX 1

Cerro del Pueblo facies and interpretations

Facies 1

Description: Fine-to-medium grained sandstone; tabular bodies thicken upwards from Parras Shale; bodies are up to 25 m thick and consist of multistoried sets (1.5–2.5m thick); sharp lower and upper contacts; tan (10YR 5/4), grey with local brown Fe-staining; predominantly massive to planar stratification with local wedge shaped sets of vague hummocky and swaley cross bedding especially in lower one-half; meso-scale trough cross-beds in upper one-half; internal erosion surfaces; Fe-stained invertebrate traces (*Thalasinoides*, *Ophiomorpha*), oxidized wood fragments, inoceramid shells, vertebrate microfossils (shark teeth, fish scales and vertebrae), local shell coquinas and lenses; local vertically-oriented root traces.

Preliminary interpretation: Shoaling-upward sandy shoreface succession capped and modified locally by foreshore, paleochannel, and washover facies.

Facies 2

Description: Lenticular bodies of very fine- to medium-grained sandstone; decimeters to meters thick; tan, brown and grey; sharp basal and upper contacts; rare occurrences of multi-meter thick inclined bedded sandstone; multistoried with scour-shaped internal erosion surfaces; local granule lenses, intraformational conglomerates (calcareous); lenses and pockets, and stringers of shell, wood and vertebrate hash; predominantly massive, horizontal to low-angle-inclined stratification; minor meso-scale trough and tabular cross-stratification; local Fe-stained wood impressions, vertebrate fossils; locally well-developed vertical root traces.

Preliminary interpretation: Predominantly low-sinuosity, vertically aggrading paleochannel deposits; rare occurrences of high sinuosity paleochannel deposits; deposition under upper flow regime conditions.

Facies 3

Description: Lenticular to tabular and wedge-shaped bodies of very fine- to fine-grained sandstone; decimeters to 1.5 m thick; may pass laterally into Facies 2; tan (10YR 5/4), brown, and grey; sharp basal and upper contacts; massive to horizontally laminated; may be intensely mottled and burrowed; rare macroplant impressions; other fossils include, invertebrate shell fragments, vertebrate fragments, plant fragment hash, leaf impressions, wood, root traces.

Preliminary Interpretation: Splay or washover sandstone resulting from high energy overbank flooding and/or high energy coastal storm events.

Facies 4

Description: Tabular to wavy beds of very fine- to fine-grained sandstone; 0.25–1.5 meters thick; tan (10YR 5/4); gradational to sharp lower and upper contacts; dominated by multiple sets of symmetrical ripples; invertebrate feeding/dwelling traces and vertebrate tracks and trackways common; bioturbated and mottled locally;

rare root traces; no shrinkage cracks or other evidence of desiccation events.

Preliminary interpretation: Oscillation ripples generated by wind-wave activity in shallow but extensive lower coastal plain lagoons, lakes and ponds; no evidence of seasonal dryness.

Facies 5

Description: Marine, brackish and fresh-water mollusk and charophyte concentrates; occur as massive to graded coquinas in tabular beds and lenses of fossiliferous siltstone to fine-grained sandstone 0.01–2.00 meters thick; tan (5Y 7/2), grey, brown; gradational to sharp lower and upper contacts; hosted by facies 6 and 7; local concentrates of vertebrate fossils; locally bioturbated, burrowed and mottled.

Preliminary interpretation: Fossiliferous lag deposits concentrated during erosional events.

Facies 6a

Description: Tabular beds of massive, coarsening-upward, silty to sandy calcareous mudrock and muddy very fine-grained sandstone; grey to grey-green (5Y 7/2); up to 5 m thick; local siltstone to sandstone lenses; mottled and bioturbated; locally contains minor mollusk shell and vertebrate fragments as float; well-developed iron-stained feeding and dwelling traces; locally-developed crustacean galleries; local occurrences of fine root traces (horizontal to vertical).

Interpretation: Coastal wetland setting; shallowing-upward flood deposits; close to sediment source; heavily overprinted by non-directional hydraulic reworking, bioturbation and possibly trampling.

Facies 6b

Description: Oyster shell float and normally-graded oyster shell concentrates (fragmentary to whole shells); tabular beds up to 1 m thick; locally capped by cm-scale coquinas with concave-down shell orientations; associated with identical lithologies as in facies 6a.

Preliminary interpretation: Oyster shell lags and reworked oyster reef deposits; coastal wetland setting, shallowing-upward flood deposits; heavily overprinted by non-directional hydraulic reworking, bioturbation and possibly trampling

Facies 7

Description: Tabular beds of massive to laminated, grey calcareous silty-claystone and clayey-siltstone up to 5 m thick; 5Y 6/1; coalified plant flecks common; local, very fine, vertical to horizontal root traces; $CaCO_3$-encrusted in-situ and reworked mollusk and vertebrate elements; a broad variety of pelecypods and gastropods occur in situ and as reworked fragmental float to coquinas (Facies 5 and 6); articulated to associated skeletons of dinosaurs (particularly hadrosaurs) are locally abundant; hosts small decimeter-scale siltstone to sandstone lenses.

Preliminary interpretation: Coastal flood basin setting (*e.g.*, wetlands, ponds, lakes, bayfill); original sedimentary environments heavily overprinted by bioturbation, trampling, subsequent reworking, and diagenetic alteration.

Cerro Huerta facies and interpretations

Facies 8

Description: Lenticular bodies of very fine- to medium-grained sandstone; decimeters to meters thick; tan, brown, red-brown, and grey; sharp basal and upper contacts; multistoried with scour-shaped internal erosion surfaces; local granule lenses and stringers; intraformational conglomerates (calcareous); dominated by massive to horizontal and inclined stratification; minor sets of trough and tabular cross-stratification; wavy to ripple laminated sandstone in upper one-half; local Fe-stained wood impressions, vertebrate fossils; locally well-developed vertical root traces.

Preliminary interpretation: Coastal flood basin setting (*e.g.*, wetlands, ponds, lakes, bayfill); original sedimentary environments heavily overprinted by bioturbation, trampling, subsequent reworking, and diagenetic alteration.

Facies 9

Description: Lenticular to tabular and wedge shaped bodies of very fine- to fine-grained sandstone; decimeters to 1.5 m thick; passes laterally into facies 8; tan, brown, and grey; sharp basal and upper contacts; massive to horizontally laminated, and wavy to ripple lamination; local occurrences of intraformational limestone pebble lenses and stringers with vertebrate bone fragments; may be mottled and burrowed; macroplant impressions and plant hash; local root traces.

*Preliminary interpretation:*Overbank splays; ephemeral flow conditions dominate.

Facies 10

Description: Tabular beds of massive, coarsening-upward, silty to sandy, locally pebbly, calcareous mudrock; tan, grey to grey-green (5Y 7/2); up to 2 m thick; locally granulitic, with intraformational pebbles, and rare invertebrate shell and vertebrate bone fragments; well-developed Fe-stained feeding and dwelling traces; local occurrences of vertical root traces; abundant in the lower one-third of formation.

Preliminary interpretation: Coastal wetland setting; shallowing-upward flood deposits; close to sediment source; heavily overprinted by non-directional hydraulic reworking, bioturbation and possibly trampling.

Facies 11

Description: Tabular beds of massive, silty to sandy calcareous mudrock; up to 3 m thick; grey and grey-green

(10Y 5/4, 10Y 6/2, 5GY 5/2) to red (5R 4/2, 10R 3/4, 10R 4/2); color boundaries irregular and change vertically and laterally; abundant *Planolites*, *Thalasinoides* and *Ophiomorpha* traces; local occurrences of centimeter- to decimeter-thick siltstone to sandstone lenses; local occurrences of randomly distributed glaebular to nodular, grey limestone concretions in redbeds; reduced grey strata with (1) rare ceratopsian bonebeds, (2) other vertebrate elements and fragments, (3) encrusted gastropod shells and (4) non-marine mollusk steinkerns (5) vertical root traces.

Preliminary interpretation: Coastal floodplain deposits; poorly-drained (green) to well-drained (red); locally developed caliches indicate high degree of evapotranspiration.

Facies 12

Description: Tabular beds of massive, silty to sandy calcareous mudrock; up to 3 m thick; mottled purple and grey-green; color boundaries irregular and change vertically and laterally; fine grey-green root traces particularly abundant; locally developed calcareous nodules; no fossils; bioturbated.

Preliminary interpretation: Coastal floodplain paleosol deposits; oscillating water table and variably drained; caliches indicate a high degree of evapotranspiration in paleosols.